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Indian Standard

OPTICAL FIBRES

PART 1 MEASUREMENT METHODS AND TEST PROCEDURES

Section 49 Differential Mode Delay

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BUREAU OF INDIAN STANDARDS
MANAK BHAVAN, 9 BAHADUR SHAH ZAFAR MARG
NEW DELHI 110002

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NATIONAL FOREWORD

This Indian Standard (Part 1/Sec 49) which is identical with IEC 60793-1-49 : 2006 'Optical fibres — Part 1-49: Measurement methods and test procedures — Differential mode delay' issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendation of the Fibre Optics, Fibres, Cables and Devices Sectional Committee and approval of the Electronics and Information Technology Division Council.

The text of IEC Standard has been approved as suitable for publication as an Indian Standard without deviations. Certain conventions are, however, not identical to those used in Indian Standards. Attention is particularly drawn to the following:

a) Wherever the words 'International Standard' appear referring to this standard, they should be read as 'Indian Standard'.
b) Comma (,) has been used as a decimal marker while in Indian Standards, the current practice is to use a point (.) as the decimal marker.

In this adopted standard, reference appears to certain International Standards for which Indian Standards also exist. The corresponding Indian Standards which are to be substituted in their respective places are listed below along with their degree of equivalence for the editions indicated:

International Standard	*Corresponding Indian Standard*	*Degree of Equivalence*
IEC 60793-1-1 : 2008 Optical fibres — Part 1-1: Measurement methods and test procedures — General and guidance	IS/IEC 60793-1-1 : 2008 Optical fibres: Part 1 Measurement methods and test procedures, Section 1 General and guidance	Identical
IEC 60793-1-22 : 2001 Optical fibres — Part 1-22: Measurement methods and test procedures — Length measurement	IS/IEC 60793-1-22 : 2001 Optical fibres: Part 1 Measurement methods and test procedures, Section 22 Length measurement	do
IEC 60793-1-41 : 2010 Optical fibres — Part 1-41: Measurement methods and test procedures — Bandwidth	IS/IEC 60793-1-41 : 2010 Optical fibres: Part 1 Measurement methods and test procedures, Section 41 Bandwidth	do
IEC 60793-1-42 : 2007 Optical fibres — Part 1-42: Measurement methods and test procedures — Chromatic dispersion	IS/IEC 60793-1-42 : 2007 Optical fibres: Part 1 Measurement methods and test procedures, Section 42 Chromatic dispersion	do
IEC 60793-1-45 : 2001 Optical fibres — Part 1-45: Measurement methods and test procedures — Mode field diameter	IS/IEC 60793-1-45 : 2001 Optical fibres: Part 1 Measurement methods and test procedures, Section 45 Mode field diameter	do

The technical committee has reviewed the provisions of the following International Standards referred in this adopted standard and has decided that they are acceptable for use in conjunction with this standard:

International Standard	*Title*
IEC 60793-2-10	Optical fibres — Part 2-10: Product specifications — Sectional specification for category A1 multimode fibres

(*Continued on third cover*)

Indian Standard

OPTICAL FIBRES

PART 1 MEASUREMENT METHODS AND TEST PROCEDURES

Section 49 Differential Mode Delay

1 Scope

This part of IEC 60793 applies only to multimode, graded-index glass-core (category A1) fibres. The test method is commonly used in production and research facilities, but is not easily accomplished in the field.

This standard describes a method for characterizing the modal structure of a graded-index multimode fibre. This information is useful for assessing the bandwidth performance of a fibre especially when the fibre is intended to support a variety of launch conditions such as those produced by standardized laser transmitters.

With this method, the output from a fibre that is single-mode at the test wavelength excites the multimode fibre under test. The probe spot is scanned across the endface of the fibre under test, and the optical pulse delay is determined at specified offset positions.

Two results can be produced from the same data. First, the difference in optical pulse delay time between the fastest and slowest mode groups of the fibre under test can be determined. The user specifies the upper and lower limits of radial offset positions over which the probe fibre is scanned in order to specify desired limits of modal structure. The DMD data is then compared to DMD specifications that have been determined by modeling and experimentation to correspond to a minimum EMB for a range of transmitters. Second, the optical pulse shapes can be combined using specific weights to determine a calculated effective modal bandwidth (EMBc), and by calculating a sequence of EMBc values with different sets of weights, a minimum EMBc can be calculated, corresponding to a range of transmitters.

The test quantifies the effects of interactions of the fibre modal structure and the source modal characteristics excluding the source spectral interactions with fibre chromatic dispersion. Adding the effects of chromatic dispersion and source spectral width will reduce the overall transmission bandwidth, but this is a separate calculation in most transmission models. In this test, the effects of non-zero spectral width are minimized but any residual effects will tend to increase the DMD value and decrease the EMBc value.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60793-1-1: *Optical fibres – Part 1: Measurement methods and test procedures –- General and guidance*

IEC 60793-1-22: *Optical fibres – Part 1-22: Measurement methods and test procedures – Length measurement*

IEC 60793-1-41: *Optical fibres – Part 1-41: Measurement methods and test procedures – Bandwidth.*

IEC 60793-1-42: *Optical fibres – Part 1-42: Measurement methods and test procedures – Chromatic dispersion*

IEC 60793-1-45: *Optical fibres – Part 1-45: Measurement methods and test procedures - Mode field diameter*

IEC 60793-2-10: *Optical fibres – Part 2-10: Product specifications – Sectional specification for category A1 multimode fibres*

IEC 61280-1-4: *Fibre optic communication subsystem test procedures – Part 1-4: General communication subsystems – Collection and reduction of two-dimensional nearfield data for multimode fibre laser transmitters*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

NOTE The user of this standard specifies either the maximum DMD for the outer (R_{OUTER}) and inner (R_{INNER}) limits of radial offset position over which the probe spot is scanned, or the minimum EMBc among the EMBc values calculated from a sequence of DMD weightings.

3.1
differential mode delay
DMD
the estimated difference in optical pulse delay time between the fastest and slowest modes excited for all radial offset positions between and including R_{INNER} and R_{OUTER}

3.2
effective modal bandwith
bandwidth associated with the transfer function, $H(f)$, of a particular laser/fibre combination

3.3
inner limit
R_{INNER}
outer limit
R_{OUTER}
limits of radial offset positions on the endface of the fibre under test over which the probe spot is scanned

4 Apparatus

4.1 Optical source

Use an optical source that introduces short duration, narrow spectral width pulses into the probe fibre.

The temporal duration of the optical pulse shall be short enough to measure the intended differential delay time. The maximum duration allowed for the optical pulse, characterized as full width at 25 % of maximum amplitude, will depend both on the value of DMD to be determined and the sample length. For example, if the desired length-normalized DMD limit is 0,20 ps/m over a sample of length 500 m, the DMD to be measured is 100 ps, and a pulse of duration less than ~110 ps is needed. Testing to the same DMD limit in a 10 000 m length of fibre requires measuring a DMD of 2 000 ps, and a pulse a wide as ~2 200 ps may be used. Detailed limits are given in 6.1, and may depend on the source spectral width.

Chromatic dispersion induced broadening resulting from source spectral width shall be within the limits indicated in Annex A. The requirement on spectral width may be met either by using a spectrally narrow source, or alternatively by the use of appropriate optical filtering at either the source or detection end.

The centre wavelength shall be within ±10 nm of the nominal specified wavelength.

A mode locked titanium-sapphire laser is an example of a source usable for this application.

4.2 Stability

Devices shall be available to position the input and output ends of the test specimen with sufficient stability and reproducibility to meet the conditions of 4.3 and 4.4.

4.3 Launch system

The probe fibre between the light source and test sample shall propagate only a single mode at the measurement wavelength. The mode field diameter of the probe fibre at λ shall be $(8{,}7\lambda - 2{,}39) \pm 0{,}5$ µm, where λ is the measurement wavelength in micrometers, and the mode field diameter is determined using IEC 60793-1-45. This equation produces a mode field diameter of 5 µm at 850 nm and 9 µm at 1 310 nm, which corresponds to commercially available single-mode fibres.

Ensure that the output of the probe fibre is single-mode. One method to do this is to strip higher order modes by wrapping the probe fibre three turns around a 25-mm diameter mandrel.

The output spot of the probe fibre shall be scanned across the endface of the test sample with a positional accuracy less than or equal to ±0,5 µm.

The output beam from the probe fibre shall be perpendicular to the endface of the test sample to within an angular tolerance of less than or equal to 1,0 degree.

The launch system shall be capable of reproducibly centring the output spot of the probe fibre to within ±1,0 µm.

If directly coupled to the test sample, the gap between the output end of the probe fibre and the endface of the test sample shall be no more than 10 µm.

A free space optics system of lenses or mirrors may be used to image the output spot of the probe fibre onto the endface of the test sample. When using this type of launch system, care should be taken to ensure that substantially the same modes are excited in the test fibre as would be if the beam were coupled directly from the output of the single-mode probe fibre. For example, a system of lenses or mirrors may be used to image the output of a single-mode fibre onto the end face of the test sample.

Provide means to remove cladding light from the test sample. Often the fibre coating is sufficient to perform this function. Otherwise, use cladding mode strippers near both ends of the test sample. If the fibre is retained on the cladding mode stripper(s) with small weights, care shall be taken to avoid microbending at these sites.

4.4 Detection system

Use an optical detection apparatus suitable for the test wavelength. The detection apparatus shall couple all of the guided modes from the test sample onto the detector's active area, such that the detection sensitivity is not significantly mode dependent. The detector, along with any signal preamplifier, shall respond linearly (within ±5 %) over the range of power detected.

The temporal response of the detector system, including any optional optical attenuator, shall not be significantly mode dependent.

A specific test for mode dependence is given in 6.1. Alternatively, the detector’s temporal response may be a function of offset as long as it is stable over the course of the measurement (i.e. $\Delta T_{\mathrm{PULSE}}(r)$ shall fulfil the ±5 % requirement of 6.1).

Ringing of the detector system shall be limited such that maximum overshoot or undershoot shall be less than 5 % of the peak amplitude of the detected optical signal as measured on the reference.

The waveform of the detected optical signal shall be recorded and displayed on a suitable instrument, such as a high-speed sampling oscilloscope with calibrated time sweep. The recording system should be capable of averaging the detected waveform for multiple optical pulses.

Use a delay device, such as a digital delay generator, to provide a means of triggering the detection electronics at the correct time. The delay device may trigger the optical source, or be triggered by it. The delay device may be internal or external to the recording instrument.

The combined effect of timing jitter and noise in the detection system shall be small enough that the difference between successive measurements of optical delay times for any fixed launch used in the measurement shall be less than 5 % of the measured value of DMD. Averaging the detected waveform for multiple optical pulses may be used to reduce the effects of timing jitter and noise. If averaging is used, each waveform shall be recorded using at least the number of averages used when determining $\Delta T_{\mathrm{PULSE}}$ in 6.1 The system shall maintain this level of stability over the course of the measurement.

4.5 Computational equipment

This test method generally requires a computer to store the intermediate data and calculate the test results.

5 Sampling and specimens

5.1 Test sample

The test sample shall be graded-index glass-core (category A1) multimode fibre.

5.2 Specimen endfaces

Prepare flat endfaces at the input and output ends of the specimen.

5.3 Specimen length

The length of the fibre shall be measured using a suitably accurate method such as that of IEC 60793-1-22.

5.4 Specimen packaging

Support the test fibre in a manner that relieves tension and minimizes microbending.

5.5 Specimen positioning

Position the input end of the test sample such that it is aligned to the output end of the launch system as described in 4.3.

Position the output end of the test sample such that it is aligned with the detection system, as described in 4.4.

6 Procedure

6.1 Adjust and measure system response

Couple the output of the probe fibre into the detection apparatus. This may be accomplished by mounting the probe fibre in the detection apparatus, or by using a short (<10 m) length of fibre mounted between the launch system and the detection system, or by directly coupling the probe output to the detector via a system of lenses and mirrors. If using a short fibre, it shall be of the same type fibre as the test fibre.

Adjust the amplitude of the optical pulse to match the smallest peak amplitude expected from the test fibre during the measurement. The smallest peak amplitude from the test fibre will usually occur for the largest radial offset.

Adjust the time scale of the detection system to match the time scale used in acquiring data from the test sample to ensure that the entire pulse is captured (see 6.2).

Measure the waveform of the optical pulse, and determine its temporal width at 25 % of the peak amplitude. This value will be used to calculate the test results, and will be called $\Delta T_{\mathrm{PULSE}}$. Linear interpolation may be used between successive time points to calculate $\Delta T_{\mathrm{PULSE}}$ for improved accuracy.

- Repeated measurements of $\Delta T_{\mathrm{PULSE}}$ shall differ by no more than 5 % of the value of DMD being measured
- If using either a short length of fibre, or a system of lenses and mirrors, the values of $\Delta T_{\mathrm{PULSE}}$ shall differ by no more than 5 % from the values obtained by coupling the probe fibre directly into the detection apparatus.
- To test and verify that the detector apparatus is not significantly mode dependent, prepare a special short-length test sample of the same type as the fibre to be tested. Measure the value of $\Delta T_{\mathrm{PULSE}}$ for each radial offset to be used in the measurement. This value shall meet the requirement of 6.1.

Use Annex A to calculate a value of ΔT_{REF} appropriate for the values of $\Delta T_{\mathrm{PULSE}}$, source spectral width, and fibre chromatic dispersion.

6.2 Adjust detection system

Launch light from the probe fibre into the test fibre. Adjust the time scale and trigger delay of the detection system such that one entire optical pulse is displayed for all relevant offsets of the probe spot, including all leading and trailing edges having amplitude greater than or equal to 1 % of the peak amplitude. All data from the test fibre shall be obtained without further adjustment of the delay and time scale.

Find the centre of the core of the test fibre. One method for finding the centre is to scan the position of the probe spot across the face of the test fibre. Find both edges of the core of the fibre along some arbitrary “x” axis, with the edge defined as the position for which the total received power reaches a threshold of about 15 % of maximum. Centre the probe spot along the “x” axis. Now scan the probe spot along the orthogonal “y” axis, finding the fibre core edges and centering along the “y” axis. Iterate, as necessary, to achieve the required positional tolerance. When the probe spot is centred, the DMD will be symmetric between positive and negative offsets along the “x” or “y” axes. IEC 61280-1-4 also describes another method for finding the optical centre of the fibre (see 5.4 of IEC 61280-1-4).

6.3 Measure the test sample

Measure the response of the test sample, $U(r,t)$, for radial offsets, r, of the probe spot. For measurement of DMD, r ranges from $R_{\mathrm{INNER}} \leq r \leq R_{\mathrm{OUTER}}$ at intervals of ≤2 µm. R_{INNER} and R_{OUTER} shall be provided in the specification (see item 3 in clause 9). Depending on the values specified for R_{INNER} and R_{OUTER}, intervals less than 2 µm may be required.

Example: If the specification calls for $R_{\mathrm{INNER}} = 0$ and $R_{\mathrm{OUTER}} = 17$ µm, the fewest number of radial offsets will be ten. Either (0, 2, …, 16, 17) µm or (0, 1, …, 15, 17) µm would meet the minimum requirement. Alternatively, one could use 18 offsets at (0, 1, 2, …, 16, 17) µm.

For EMBc measurements, scan from the optical centre to within 1 µm of the nominal core radius. Additional radial offsets may be used. For 50 µm core diameter A1a.2 multimode fibre EMBc measurements, measure $U(r,t)$ over the range $0 \leq r \leq 24$ µm at intervals of ≤2 µm.

At each radial offset, measure the waveform of the optical pulse, and determine the temporal position of the leading and trailing edges at 25 % of the maximum amplitude of the resulting waveform (see Annex B). Linear interpolation may be used between successive time points to estimate the leading and trailing edge times for improved accuracy. Record the leading and trailing edge times for each radial offset position.

7 Calculations and interpretation of results

The minimum *effective modal bandwidth* (EMB) of a fibre is the minimum bandwidth corresponding to excitation from transmitters conforming to defined launch conditions. For example, the minimum EMB specified in IEC 60793-2-10 is applicable to launch conditions also specified in IEC 60793-2-10. The minimum EMB is determined by calculating either the DMD or the minimum calculated EMB (EMBc). The purpose of either calculation is to ensure that the EMB of the fibre will exceed the requirement for any mode power distribution consistent with conforming transmitters. The conformance of the transmitters may be defined, for example, by encircled flux requirements such as those found in IEC 60793-2-10 measured by IEC 61280-1-4.

7.1 Differential mode delay (DMD)

Find T_{FAST}, the minimum of the leading edge times for excitation between R_{INNER} and R_{OUTER} from among the output pulses recorded in 6.3.

Find T_{SLOW}, the maximum of the trailing edge times for excitation between R_{INNER} and R_{OUTER} from among the output pulses recorded in 6.3.

Calculate DMD:

- Option 1 (See Annex B):

  Using the value of ΔT_{REF} from 6.1, DMD = $(T_{\text{SLOW}} - T_{\text{FAST}}) - \Delta T_{\text{REF}}$

  The lower reporting limit for DMD using this equation is $0{,}9(\Delta T_{\text{REF}})$ because of the practical measurement problems discussed in Annex B. Consequently, if the value calculated for DMD using the above equation is less than $0{,}9(\Delta T_{\text{REF}})$, report the result as being "less than $0{,}9(\Delta T_{\text{REF}})$".

- Option 2

  DMD can alternatively be calculated by deconvolving the reference pulse from the pulses gathered exiting the test fibre. To utilize deconvolution, the algorithm shall not introduce significant error for the pulse shapes encountered in the measurement, especially arising from the choice of a high-frequency noise filter.

- Multiple DMD values

  A fibre may be characterized by multiple DMD values, with each value evaluated for a different range of R_{INNER} and R_{OUTER}. In this case, all DMD values may be evaluated from among the output pulses recorded in 6.3, provided that the radial offset requirements of 6.3 are met for each of the ranges of R_{INNER} and R_{OUTER}.

7.2 Minimum calculated effective modal bandwidth

The *minimum EMBc* is the minimum value of EMBc determined for a specific fibre using the full set of weightings corresponding to a range of mode power distributions using the calculations of 7.2.1 to 7.2.4.

The *DMD weightings* correspond to the range of mode power distributions consistent with the launch condition specifications of the optical transmitters utilized in the application. They are specified by the user's detailed specification. The user may also specify an additional multiplier that is used to align EMBc to the theoretical effective modal bandwidth required by the application. A default set of weightings applicable to, for example, IEEE 802.3 10GBASE-S and INCITS 364 10GFC is specified in IEC 60793-2-10 and is also included as an example in Annex D of this document. Annex C provides a procedure for generating DMD weights from encircled flux data.

The following calculations involve the use of weight functions that are derived from near-field encircled flux data of laser sources that are characteristic of applications. For a given fibre, the application of several weight functions will yield a number of EMBc values, the minimum of which is the minimum EMBc for the fibre.

NOTE When DMD data are collected at offsets separated by 2 µm, the $U(r,t)$ values at the intervening 1 µm offsets may be interpolated for the purpose of these calculations.

7.2.1 Calculate the output pulse

Calculate a resultant output temporal response, $P_o(t)$ utilizing the fibre output pulse information and a weighting function.

$$P_o(t) = \sum_r W(r)U(r,t) \tag{1}$$

where

$U(r,t)$ is the sample output pulse measured at each radial offset r as a function of time t. Each output pulse is raw (un-normalized in amplitude), after an appropriate subtraction of baseline noise;

$W(r)$ is the DMD weighting function corresponding to the transmitter used in the application (see Annex C for details on calculating $W(r)$, and see Annex D for example $W(r)$ values corresponding to a particular launch specification)

7.2.2 Calculate the transfer function

Deconvolve the reference temporal response, $R(t)$, from the resultant output response, $P_o(t)$, in a similar fashion to that done in bandwidth measurements described in IEC 60793-1-41. This gives the fibre frequency response, $H_{Fib}(f)$, also called the *fibre transfer function.*

$$H_{Fib}(f) = FT\{P_O(t)\} / FT\{R(t)\} \tag{2}$$

where:

$P_o(t)$ is the resultant output pulse from 7.2.1;

$R(t)$ is the resultant reference pulse from 6.1;

FT is the Fourier transform function.

NOTE These calculations yield an array of complex numbers.

7.2.3 Calculated effective modal bandwidth (EMBc)

Calculate the –1,5 dB optical bandwidth. It is determined from the lowest frequency where the magnitude of the transfer function is 1,5 dB down from the zero frequency value. The –1,5 dB optical value is then extrapolated to –3 dB using Gaussian assumptions by multiplying it by 1,414.

NOTE The bandwidth can be determined by the traditional 3 dB definition (the first point at which the transfer function, $H_{Fib}(f)$ reaches 50 % or 3 dB). However, highly non-Gaussian responses can be generated using real fibre and real sources. For these responses, the measured 3 dB value has been shown not to provide a good correlation to system performance. The 1,5 dB metric addresses some of the limitations of a wavy transfer function and its effect on the –3 dB value.

7.2.4 System stability frequency limit (SSFL)

Define

$$G_{\text{ref}}(f) = \frac{FT(R_A(t))}{FT(R_B(t))} \tag{3}$$

where

R_A and R_B are two independent reference pulses;

SSFL is the minimum frequency where $|G(f)|$ exceeds 1,0 ± 0,05 (see 60793-1-41).

If the EMBc calculated for a fibre/laser combination exceeds the SSFL, report the normalized bandwidth value as *greater than SSFL × length*.

7.3 Length normalization

It may be desirable to normalize the value of DMD or EMBc to a unit length, such as ps/m or MHz·km. If normalization to a unit length is used, the length dependence formula shall be reported.

8 Documentation

8.1 Report the following information for each test:

- test sample identification;
- test sample length;
- length normalization formula, if used;
- test date;
- source wavelength (nominal or actual);
- minimum and maximum radial offsets, R_{INNER}, R_{OUTER};
- test result: DMD(R_{INNER}, R_{OUTER}) and/or minimum EMBc.

8.2 The following information shall be available upon request:

- the measurement method used;
- description of the test equipment, including: source type and actual source centre wavelength, maximum specified or actual spectral width (r.m.s.);
- for DMD measurement, documentation of method used to calculate ΔT_{REF} . For minimum EMBc, the transfer function features that are used to determine bandwidth, and the set of weightings used;
- detector type and operating conditions;
- mode field diameter of probe fibre at measurement wavelength (nominal or actual);
- method of stripping cladding light;
- date of latest calibration of test equipment.

9 Specification information

When specifying fibre performance using this test method, the following information shall be specified:

- number and type of samples to be tested;
- test procedure (IEC 60793-1-49);
- test wavelength(s);

- DMD requirements: Required DMD value for a stated range of minimum and maximum radial offsets, DMD(R_{INNER}, R_{OUTER}). Evaluation of several different DMD values for different stated ranges in R_{INNER} and R_{OUTER} may be required;
- for DMD measurements, reporting method option from 7.1;
- for EMBc requirements: Required minimum EMBc value;
- for EMBc requirements: Required set of weights per Annex C.

Annex A
(normative)

Source spectral width limitation

A.1 Limiting the effect of chromatic dispersion on the value of DMD

The effect of errors introduced by chromatic dispersion on the value of DMD shall be less than 10 %. This requirement may be met either by using a source with a spectral width small enough that chromatic dispersion can be ignored, or by accurately determining the spectral shape of the source and calculating the appropriate value of ΔT_{REF}.

The chromatic dispersion $D(\lambda)$ may be estimated using the data given in Clause A.2. Alternatively, one may use $D(\lambda)$ obtained using IEC 60793-1-42 for the particular type of fibre being tested. The requirement on spectral width may be met either by using a spectrally narrow source, or by using an optical filter at either the source or detection end.

Several examples of methods for meeting the requirement of this annex are now given.

A.1.1 Use a source with sufficiently narrow spectral width such that the value of

$$\Delta t_{\mathrm{chrom}} = 4 \cdot \sqrt{\ln(2)} \cdot \delta\lambda \cdot D(\lambda) \cdot L \tag{A.1}$$

is less than 10 % of the DMD to be measured. This gives a constraint on r.m.s. spectral width $\delta\lambda$,

$$\delta\lambda \le \frac{0{,}1 \cdot \mathrm{DMD}_{\mathrm{min}}}{4\sqrt{\ln(2)} \cdot D(\lambda) \cdot L} = 0{,}030 \cdot \frac{\mathrm{DMD}_{\mathrm{min}}}{D(\lambda) \cdot L} \tag{A.2}$$

Here, DMD_{min} is the smallest value of DMD to be determined, $D(\lambda)$ is the chromatic dispersion, and L is the sample length. Under the typical assumption that the modal delays of a fibre scale linearly with length, this constraint has no length dependence.

Use $\Delta T_{\mathrm{REF}} = \Delta T_{\mathrm{PULSE}}$ in 6.1. and for calculating the value of DMD.

Example: DMD values as small as 100 ps are to be tested on fibre lengths of 0,5 km at a wavelength of 850 nm. From Table A.1 in A.2, the value of $D(\lambda)$ at 850 nm is 107 ps/nm-km. Substituting this information in equation (A.2), the source r.m.s. spectral width $\delta\lambda$ should be ≤ (0,03 × 100 ps)/(107 ps/nm-km × 0,5 km) = 0,056 nm. The same source would work for a 10 km test length with DMD values as low as 2 000 ps.

A.1.2 Use a source with sufficiently narrow spectral width that ignoring Δt_{chrom} in relation to ΔT_{PULSE} changes the value of ΔT_{REF} by less than 10 %. This gives a constraint on r.m.s. spectral width $\delta\lambda$,

$$\delta\lambda \le \frac{\sqrt{0{,}21}\cdot\Delta T_{\text{PULSE}}}{4\sqrt{\ln(2)}\cdot D(\lambda)\cdot L} = 0{,}138\cdot\frac{\Delta T_{\text{PULSE}}}{D(\lambda)\cdot L} \qquad \text{(A.3)}$$

Use $\Delta T_{\text{REF}} = \Delta T_{\text{PULSE}}$ in 6.1, and for calculating the value of DMD.

In this case, there is no explicit dependence of source spectral width $\delta\lambda$ on the value of DMD being measured. Instead, the minimum value of DMD that can be measured is set directly by ΔT_{PULSE}. Note that there is an explicit dependence of the maximum allowed spectral width on sample length. For fixed spectral width, chromatic broadening will become too large to ignore above a certain sample length.

Example: A particular laser source and optical detector having the value ΔT_{PULSE} = 60 ps are used to measure 0,5 km samples at 850 nm. Substituting this information into equation (A.3), the source r.m.s. spectral width $\delta\lambda$ should be ≤ (0,138 × 60 ps)/(107 ps/nm-km × 0,5 km) = 0,15 nm.

A.1.3 Calculate the appropriate value of ΔT_{REF} for the source being used. ΔT_{REF} is the full width at 25 % of each mode at the output of the fibre under test. For near-Gaussian pulse and spectral shapes use,

$$\Delta T_{\text{REF}} = \left(\Delta T_{\text{PULSE}}^2 + \Delta t_{\text{chrom}}^2\right)^{1/2} \qquad \text{(A.4)}$$

In this case, the upper limit on the spectral width of the source is set indirectly by the requirement in 7.1 that the minimum value of DMD reported by the measurement is 0,9(ΔT_{REF}).

If a source has multiple spectral peaks, or is otherwise sufficiently non-Gaussian, this formula may be inaccurate. If equation (A.4) is used to calculate the value of ΔT_{REF}, the error introduced to the calculation of DMD must be less than 10 %.

A.2 Chromatic dispersion in multimode fibres

The data in Table A.1 represents the highest expected dispersion for any of the commercially available Category A1 fibres, based on nominal dispersion performance and numerical aperture (NA). At wavelengths lower than 1 200 nm, dispersion is greatest with fibre having maximum λ_0 (0,29 NA fibre). At wavelengths greater than 1 400 nm, dispersion is greatest with fibre having minimum λ_0 (0,20 NA fibre). Here λ_0 is the zero-dispersion wavelength. Table A.1 is not used for wavelengths between 1 200 and 1 400 nm. Instead, use D = 16,6 ps/nm-km.

Table A.1 –Highest expected dispersion for any of the commercially available Category A1 fibres

λ (nm)	***D*** (ps/nm-km)	λ (nm)	***D*** (ps/nm-km)	λ (nm)	***D*** (ps/nm-km)
780	146				
790	140				
800	133	1 000	54,2	1 400	8,28
810	128	1 010	51,8	1 410	9,08
820	122	1 020	49,2	1 420	9,85
830	117	1 030	46,9	1 430	10,6
840	112	1 040	44,7	1 440	11,4
850	107	1 050	42,5	1 450	12,1
860	102	1 060	40,3	1 460	12,8
870	98,0	1 070	38,2	1 470	13,5
880	93,7	1 080	36,2	1 480	14,2
890	89,7	1 090	34,3	1 490	14,9
900	85,7	1 100	32,4	1 500	15,6
910	82,1	1 110	30,6	1 510	16,2
920	78,4	1 120	28,9	1 520	16,9
930	75,0	1 130	27,2	1 530	17,5
940	71,6	1 140	25,5	1 540	18,1
950	68,6	1 150	23,9	1 550	18,8
960	65,5	1 160	22,4	1 560	19,4
970	62,5	1 170	20,8	1 570	20,0
980	59,6	1 180	19,4	1 580	20,6
990	57,0	1 190	17,9	1 590	21,1
				1 600	21,7

Assumptions:

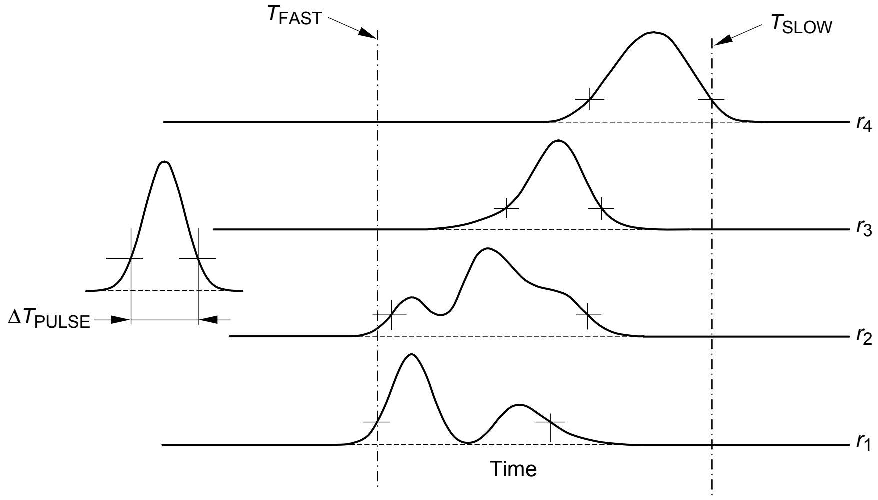
- for $\lambda < 1\,200$ nm: S_0 =0,09562 ps/(nm^2 ·km); λ_0 = 1 344,5 nm for a nominal multimode fibre with 0,29 NA;
- for $\lambda > 1\,400$ nm: S_0 =0,101 ps/(nm^2 ·km); λ_0 = 1 310 nm for a nominal multimode fibre with 0,20 NA.

Annex B
(informative)

Discussion of measurement details

B.1 DMD

This standard focuses on determining the difference in delay times between the fastest and slowest mode groups excited for a stated range of excitation conditions, as illustrated in Figure B.1. The DMD data resulting for these measurements may be compared to DMD specifications that have been determined by modeling and experimentation to correspond to a minimum EMB for a range of transmitters.



Leading and trailing edge times (25% threshold) are identified with "+". Traces are offset for different excitation positions. Inset shows ΔT_{PULSE}.

Figure B.1 – Idealized DMD data

For any given offset position, the spot from the single-mode probe excites several different mode groups. The resulting output waveform, $U(r,t)$, exhibits a complicated time dependence, typically showing multiple peaks, and with no guarantee that the individual mode groups will be clearly resolved. The detection level for the leading and trailing edges is chosen at 25 % of peak amplitude of a given waveform. This accounts for instances when the mode group maximally excited by the probe spot at a given offset is separated in time from the other mode groups excited at the same offset. The 25 % level assures detection of the separated mode group even when the other modes all have the same delay time, causing their combined amplitude to exceed that of the separated mode group.

The difference between T_{SLOW} and T_{FAST} will be greater than the DMD by an amount that depends on the temporal width of the optical pulse, the finite bandwidth of the optical detector, and the broadening of each mode due to the source spectral width and the chromatic dispersion of the fibre under test.

The temporal width of the optical pulse and the finite detector bandwidth are characterized as ΔT_{PULSE}. In the limit of small ΔT_{PULSE}, and assuming a Gaussian shape for the spectrum of the source, the temporal width at 25 % of maximum of each mode at the output of the fibre under test will be

$$\Delta t_{\text{chrom}} = 4 \cdot \sqrt{\ln(2)} \cdot \delta\lambda \cdot D(\lambda) \cdot L\,, \tag{B.1}$$

where

$\delta\lambda$ is the r.m.s. spectral width of the source (in nm),

$D(\lambda)$ is the chromatic dispersion (in ps/(nm-km) and

L is the sample length (in km).

The factor $4 \cdot \sqrt{\ln(2)}$ comes from the use of 25 % of maximum amplitude as the threshold for evaluating DMD, along with the use of r.m.s.. spectral width in characterizing the source.

The full width at 25 % of each mode at the output of the fibre under test is then

$$\Delta T_{\text{REF}} = \left(\Delta T_{\text{Pulse}}^2 + \Delta t_{\text{chrom}}^2\right)^{1/2} \tag{B.2}$$

and the DMD is given by

$$\text{DMD} = (T_{\text{SLOW}} - T_{\text{FAST}}) - \Delta T_{\text{REF}} \tag{B.3}$$

Note that while ΔT_{PULSE} is fixed by the duration of the optical pulse and the detector bandwidth, the value of Δt_{chrom} varies with the sample length. Limiting the effect of chromatic dispersion involves using a source with a value of $\delta\lambda$ that depends on the value of DMD being measured, the length of sample being measured, and the value of ΔT_{PULSE}, as detailed in Annex A.

Since the determination of DMD involves comparing the delay times from different waveforms from measurements made at different offset positions, jitter in the timing or duration of the probe pulse is a potential problem. The lower reporting limit for DMD, $0{,}9(\Delta T_{\text{REF}})$, assures an error of <10 %, limited primarily by the total system jitter.

In the course of developing this measurement procedure, use of deconvolution of the system response with the detected optical pulses was considered as a method of evaluating T_{FAST} and T_{SLOW}. However, given the relatively coarse limit on the smallest value of DMD that can be measured, there is no advantage to be gained from using a more complicated deconvolution method. Errors from using simple subtraction of ΔT_{REF} are less than 1 % for DMD $\geq 0{,}9(\Delta T_{\text{REF}})$.

B.2 EMBc Calculation

The idea behind the EMBc calculation is to use the DMD pulse information to predict the effect of pulse spread due to intermodal dispersion when the fibre is used with actual transmitters. By generating a weighted sum of the DMD pulses, the effects of different mode group power distributions of different transmitters can be examined to determine a representative worst-case pulse shape via Fourier Transform to the frequency domain. By including a range of actual mode power distributions, but only those corresponding to transmitters conforming to a launch specification, the performance of the fibre can be measured for such launch specification without unnecessarily restricting the fibre.

The effective modal bandwidth (EMB) of a fibre depends by definition only on the modal delays and the modal power weighting. It is usually assumed that there is complete coupling within a mode group so that mode group delays will determine the EMB (and in fact, the performance of an actual fibre with an actual transmitter). It is further assumed that there is no coupling between mode groups. If the mode group delays and their relative power for group g are denoted by τ_g and P_g, respectively, then the complex transfer function from which the EMB is determined has the relatively simple form

$$H(f) = \sum_g P_g \exp(i 2\pi f \Delta\tau_g) \tag{B.4}$$

where

$\Delta\tau_g = \tau_g - \tau_{ave}$ and

τ_{ave} is the centroid of the mode groups given by $\tau_{ave} = \sum_g P_g \tau_g$.

The amplitude $|H(f)|$ from which the bandwidth is customarily calculated has the form:

$$|H(f)| = \sqrt{\left[\left(\sum_g P_g \cos(2\pi f \Delta\tau_g)\right)^2 + \left(\sum_g P_g \sin(2\pi f \Delta\tau_g)\right)^2\right]} \tag{B.5}$$

The standard definition of bandwidth (IEC 60793-1-41) for multimode fibres is the –3 dB frequency f where $|H(f)|$ first reaches 0,5. In practice, depending on the mode delays and their relative power, $|H(f)|$ may have waves and plateaus so that the –3 dB bandwidth may not be robust to small changes in the mode power distribution seen in practice. This is well known [1, 2]1). The –1,5 dB bandwidth is more robust with respect to these characteristics.

The calculation of EMBc has three steps:

(1) Each DMD measurement pulse $U(r,t)$ taken at an offset of r µm is given a relative weight W_r and the sum of the weighted pulses gives a weighted output pulse $P_o(t)$.

(2) The effect of the reference on the output pulse is removed using a deconvolution similar to that used in the bandwidth measurement (IEC 60793-1-41). This gives the fibre frequency response or transfer function, the complex function $H(f)$ above.

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1) Figures in squares brackets refer to the Bibliography.

(3) EMBc is determined from the complex transfer function as described in 7.2.2 using the –1,5 dB bandwidth value.

For a specific fibre, steps 1-3 are repeated with a set of weightings, corresponding to a set of mode power distributions, and the minimum EMBc determined from the set is a measure of the minimum performance of the fibre with a set of transmitters corresponding to the weightings. It is not necessary that every weighting correspond to an actual transmitter.

The approach to specifying performance for a given fibre in terms of EMBc is made robust by the use of minimums and the use of an adjusted bandwidth. Effectively, this provides an estimate of the worst case EMB (and hence, in the link model, of inter-symbol interference (ISI) penalty performance) as long as a broad enough set of weightings is included and the range of launch distributions spans the range allowed for a given application. Typically, if the transmitter launch distributions are sufficiently unique and distributed across the allowed launch distribution range, 5-10 weightings (corresponding roughly to 5-10 transmitters) are sufficient to determine the minimum EMBc.

Annex C
(informative)

Determining DMD weights for EMBc calculation

C.1 Selecting a set of weightings

The weightings for an individual EMBc calculation can be denoted by the vector *W_r*, where *r* is the offset of the DMD. The set of weightings needed to calculate the minimum EMBc can be denoted by a matrix *W_rL*, where *L* corresponds to a specific weighting. The specific weighting may be linked to a specific transmitter which is being 'modelled', or it may be a purely theoretical weighting. The connection to a specific transmitter needs to be understood as approximate because the weighting only duplicates one feature of the transmitter, the mode power distribution. Nevertheless, by calculating the minimum EMBc with a broad range of weightings, approximating a broad range of transmitters, the fibre can be assured of a minimum EMB with actual transmitters.

The set of weightings shall be specific for the transmitter specifications and for the bit rate requirements (bandwidth requirements). Annex D contains an example set of DMD weightings.

C.2 Procedure for generating DMD weightings given encircled flux data.

To generate the appropriate DMD weighting corresponding to encircled flux data for a particular transmitter, taken according to IEC 61280-1-4:

a) convert the encircled flux data to a calculated mode power distribution P_g ;

b) convert the mode power distribution P_g to a DMD weighting W_r .

The methods summarized here provide for the calculation of a mode power distribution (MPD) from encircled flux data, and for calculation of DMD weightings from the mode power distribution. Given DMD weightings, it is straightforward to reverse the calculation and calculate the mode power distribution from the DMD weightings and then the near field intensity (or encircled flux) from the mode power distribution. The methods assume that the encircled flux measured at the far end of a 10 m piece of fibre adequately represents the mode power distribution of the source.

The encircled flux measured according to IEC 61280-1-4 and the near field intensity are related by the equation

$$EF(r) = \frac{\int_0^r I(r) r dr}{\int_0^{r_{\max}} I(r) r dr} \tag{C.1}$$

where

r is the radial offset

r_{max} is typically 1,15 the core radius

The calculation of the DMD weighting, W_r, is a two-step process:

(1) from the near field intensity, I_r, calculate the mode power distribution, P_g.;

(2) from the mode power distribution, P_g, calculate the weighting function, W_r.

The MPD is estimated from the near field measurement, assuming full coupling within a group, incoherence, and that the transmitted near field is well approximated by the measured nearfield on a short length of fibre. In this case there is a connection between the nearfield intensity $I(r)$ and the modal weighting functions of the scalar wave equation:

$$I(r) = \sum_{m} P_m \Psi^2{}_m(r) \tag{C.2}$$

Here the MPD is written in terms of the individual modes before any coupling occurs. Because of the large number of individual modes (and other reasons) it is not feasible to solve for the individual modes, but if coupling within a group is assumed, then:

$$P_g \Psi^2{}_g(r) = \sum_{m \in G} P_m \Psi^2{}_m(r) \tag{C.3}$$

and we need to solve for P_g from the equation:

$$I(r) = \sum_{g} P_g \Psi^2{}_g(r) \tag{C.4}$$

$\Psi^2{}_g(r)$ is known theoretically, and the P_g can be solved by a least squares procedure given a known $I(r)$.

Once P_g is known, the weighting function W_r is related to it by a matrix, P_{rg}, which gives the relative power in mode group g for a DMD offset at position r [3, 4]. At this point, a second least squares equation needs to be solved:

$$P_g = \sum_{r} W_r P_{rg} \tag{C.5}$$

This approach and its variants below are aligned with the 10 GbE EMB modelling, which used the modal power distribution P_g for 2 000 theoretically constructed lasers .

NOTE 1 The W_r calculated in this way should zero the Mode Power P_g in the last two mode groups (groups 18 and 19 in 10 GbE model) to account in a standard way for differential mode attenuation, as was done in the TIA modelling.

NOTE 2 If in the course of calculating P_g negative values should arise, they should be set to zero before calculating W_r. If, in turn, negative values of W_r should arise, they should be set equal to zero. An iterative least squares procedure constraining W_r and P_g to be positive will avoid this problem.

Annex D
(informative)

EMBc calculation information

D.1 Default DMD weightings for transmitters conforming to IEC 60793-2-10

The example set of weightings in Tables D.1 and D.2 are specific to transmitters meeting the requirements of Annex D.1 of IEC 60793-2-10:2004, such as those of the IEEE 802.3 application for 10GBASE-SR and the fibre channel application of INCITS 364 10GFC. Weightings are provided for a DMD measured at 1µm intervals, for 10 lasers corresponding to the range actually seen.

Table D.1 – DMD weightings – Example set 1

	Laser ID				
r	1	2	3	4	5
0	0	0	0	0	0
1	0,033 023	0,023 504	0	0	0
2	0,262 463	0,188 044	0	0	0
3	0,884 923	0,634 634	0	0	0
4	2,009 102	1,447 235	0,007 414	0,005 637	0,003 034
5	3,231 216	2,376 616	0,072 928	0,055 488	0,029 856
6	3,961 956	3,052 908	0,262 906	0,200 05	0,107 634
7	3,694 686	3,150 634	0,637 117	0,483 667	0,258 329
8	2,644 369	2,732 324	1,197 628	0,896 95	0,458 494
9	1,397 552	2,060 241	1,916 841	1,402 833	0,661 247
10	0,511 827	1,388 339	2,755 231	1,957 805	0,826 035
11	0,110 549	0,834 722	3,514 797	2,433 247	1,000 204
12	0,004 097	0,419 715	3,883 317	2,639 299	1,294 439
13	0,000 048	0,160 282	3,561 955	2,397 238	1,813 982
14	0,001 111	0,047 143	2,617 093	1,816 953	2,506 95
15	0,005 094	0,044 691	1,480 325	1,296 977	3,164 213
16	0,013 918	0,116 152	0,593 724	1,240 553	3,572 113
17	0,026 32	0,219 802	0,153 006	1,700 02	3,618 037
18	0,036 799	0,307 088	0,012 051	2,240 664	3,329 662
19	0,039 465	0,329 314	0	2,394 077	2,745 395
20	0,032 152	0,268 541	0	1,952 429	1,953 241
21	0,019 992	0,166 97	0	1,213 833	1,137 762
22	0,008 832	0,073 514	0	0,534 474	0,494 404
23	0,002 612	0,021 793	0	0,158 314	0,146 517
24	0,000 282	0,002 679	0	0,019 738	0,018 328
25	0	0	0	0	0

Table D.2 – DMD weightings – Example set 2

	Laser ID				
r	6	7	8	9	10
0	0	0	0	0	0
1	0,015 199	0,0162 53	0,022 057	0,0104 3	0,015 681
2	0,120 91	0,129 011	0,176 39	0,083 496	0,124 978
3	0,407 702	0,434 844	0,595 248	0,281 802	0,421 548
4	0,925 664	0,987 184	1,351 845	0,650 28	0,957 203
5	1,488 762	1,587 6	2,174 399	1,130 599	1,539 535
6	1,825 448	1,946 614	2,666 278	1,627 046	1,887 747
7	1,702 306	1,815 285	2,486 564	2,044 326	1,762 955
8	1,218 378	1,299 241	1,780 897	2,291 72	1,292 184
9	0,643 911	0,686 635	0,945 412	2,280 813	0,790 844
10	0,238 557	0,255 85	0,360 494	1,937 545	0,559 38
11	0,098 956	0,131 429	0,163 923	1,383 006	0,673 655
12	0,204 274	0,327 091	0,318 712	0,878 798	1,047 689
13	0,529 982	0,848 323	0,778 983	0,679 756	1,589 037
14	1,024 948	1,567 513	1,383 174	0,812 36	2,138 626
15	1,611 695	2,224 027	1,853 992	1,074 702	2,470 827
16	2,210 689	2,555 06	1,914 123	1,257 323	2,361 764
17	2,707 415	2,464 566	1,511 827	1,255 967	1,798 213
18	2,938 8	2,087 879	0,908 33	1,112 456	1,059 264
19	2,739 32	1,577 111	0,386 991	0,879 309	0,444 481
20	2,090 874	1,056 343	0,111 76	0,608 183	0,123 304
21	1,261 564	0,595 102	0,014 829	0,348 921	0,012 552
22	0,552 14	0,256 718	0,001 818	0,151 12	0
23	0,163 627	0,076 096	0,000 54	0,044 757	0
24	0,020 443	0,009 446	0	0,005 639	0
25	0	0	0	0	0

D.2 Example method to determine if an adjusted BW metric is adequate

One method to determine if an adjusted BW metric is adequate is to make use of the TIA 10 GbE modelling work [5] and the simulation of the 40 000 links, including EMB and ISI. The full transfer function can be calculated for each of the 10 000 straight links with no connectors. If the EMB, calculated with –3 dB BW or an adjusted BW, is greater than 2 000 MHz·km, then the fibre should also pass the ISI requirement of 2,6 dB. A number of fibres either pass –3 dB BW >2 000 MHz·km and fail ISI, or fail 2 000 MHz·km and pass ISI. An adjusted BW metric M1 is an improvement over metric M2 if it shifts the distribution of fibres so that essentially all fibres passing 2 000 MHz·km also pass ISI, but without incurring an additional penalty of extra ISI-passing fibres being shifted below 2 000 MHz·km. The exact balance between these two goals depends on other requirements, but the ideal adjusted BW metric will have no fibres in either category.

As modelling proceeds to other bit rates and lengths, a particular adjusted BW metric will be preferred if it applies in multiple situations and thus is “*scalable.*”

In order to achieve agreement between a performance metric such as measured effective bandwidth, which includes the effects of chromatic dispersion and source spectral characteristics, and predicted minimum EMBc, it may be necessary to correct the calculated transfer function for the effect of chromatic dispersion caused by the source’s spectral content. If the impact of chromatic dispersion is significant, the chromatic dispersion transfer function created by the source spectrum is convolved with the fibre transfer function calculated in 7.2.2. The chromatic dispersion transfer function is calculated by taking the source spectrum and multiplying it by the measured delay as a function of wavelength.

Annex E
(informative)

Comparison between this standard and ITU recommendations

ITU-T Recommendation G.650.1 contains no information on how to measure the DMD of a graded-index multimode fibre.

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IEC 60825-1, *Safety of laser products – Part 1: Equipment classification, requirements and user's guide*

IEC 60825-2 *Safety of laser products – Part 2: Safety of optical fibre communication systems.*

(*Continued from second cover*)

International Standard	*Title*
IEC 61280-1-4	Fibre optic communication subsystem test procedures — Part 1-4: General communication subsystems — Collection and reduction of two-dimensional nearfield data for multimode fibre laser transmitters

Only the English language text has been retained while adopting it in this Indian Standard and as such the page numbers given here are not the same as in the IEC Publication.

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